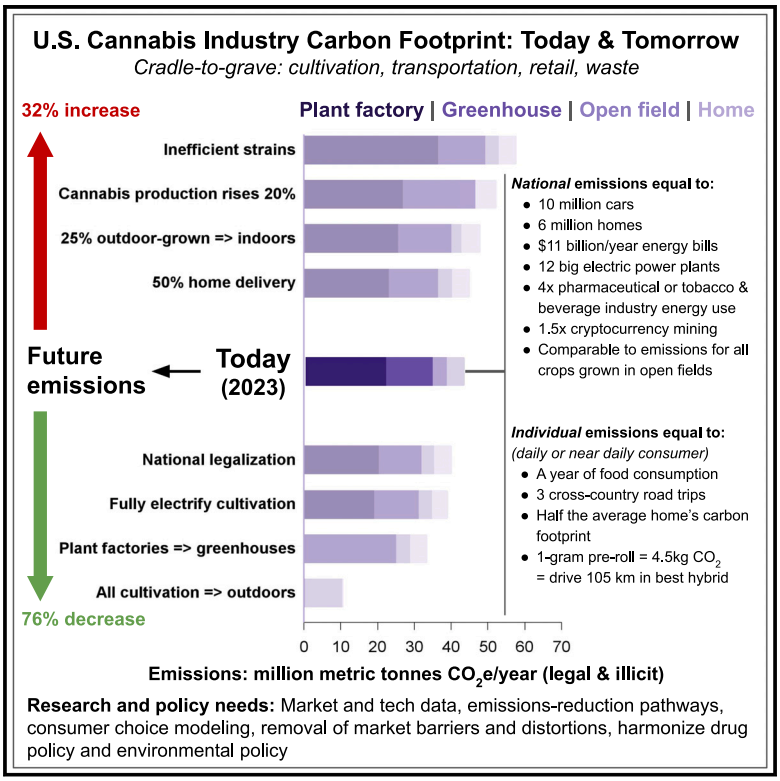
One Earth

Article

Energy-intensive indoor cultivation drives the cannabis industry's expanding carbon footprint

Graphical abstract


U.S. Cannabis Industry Carbon Footprint: Today & Tomorrow
Cradle-to-grave: cultivation, transportation, retail, waste
32% increase
Plant factory | Greenhouse | Open field | Home
Inefficient strains
Cannabis production rises 20%
25% outdoor-grown => indoors
50% home delivery
Future emissions
Today (2023)
National legalization
Fully electrify cultivation
Plant factories => greenhouses
All cultivation => outdoors
76% decrease
National emissions equal to:
10 million cars
6 million homes
$11 billion/year energy bills
12 big electric power plants
4x pharmaceutical or tobacco & beverage industry energy use
1.5x cryptocurrency mining
Comparable to emissions for all crops grown in open fields
Individual emissions equal to:
(daily or near daily consumer)
A year of food consumption
3 cross-country road trips
Half the average home's carbon footprint
1-gram pre-roll = 4.5kg CO2 = drive 105 km in best hybrid
0 10 20 30 40 50 60 70
Emissions: million metric tonnes CO2e/year (legal & illicit)
Research and policy needs: Market and tech data, emissions-reduction pathways, consumer choice modeling, removal of market barriers and distortions, harmonize drug policy and environmental policy

Highlights

- The energy-intensive cannabis industry is a major emitter of greenhouse gases
- Life cycle assessment finds that outdoor cultivation could trim emissions up to 76%
- This approach requires less land than solar PV footprint for indoor cultivation
- Legalization alone will not achieve these savings; other policies are needed

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In brief

Two-thirds of the 24,000 t/year of legal and illicit US cannabis cultivation takes place indoors. Industry-wide life cycle emissions are 44 Mt CO_2e/year, equaling those of 6 M homes or 10 M cars, ~90% of which is associated with factory-farmed products. Energy use is four times that of beverage and tobacco or pharmaceutical and medicine manufacturing. Maximal reductions can be achieved by a policy-driven shift toward more outdoor cultivation, but this requires addressing market distortions and harmonizing drug and environmental policy.

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Article

Energy-intensive indoor cultivation drives the cannabis industry's expanding carbon footprint

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SCIENCE FOR SOCIETY Unquantified greenhouse gas emissions from rapidly expanding cannabis production in the US are hampering efforts by policymakers, industry stakeholders, and consumers to address climate change. Indoor cultivation can also yield worse outcomes for indoor and outdoor air quality, power grids, waste production, water use, energy costs, worker safety, and environmental justice. Key barriers to sustainable solutions include subsidies and other market distortions, low consumer and producer awareness, embargoes on public goods research, and uncoordinated drug and environmental policies. This life cycle emissions analysis encompasses energy and other cultivation inputs, transportation, retail, and waste disposal. The resulting national emissions from legal and illicit cannabis producers are more than some other industries and nearly half of a daily consumer's household carbon footprint. Since about 90% of these emissions arise from indoor producers, policy priorities should be focused there.

SUMMARY

While the local environmental harms of cultivating cannabis outdoors receive considerable attention, those from indoor cultivation are often overlooked. Windowless plant factories and high-tech greenhouses are vastly more energy intensive than open-field cultivation, conventional buildings, and some industries. With US cannabis production more than doubling over the past decade to ~24 kt/year, the lack of greenhouse gas emissions inventories creates a serious information vacuum. This life cycle assessment finds industry-wide emissions of ~44 Mt CO_2e/year (half from legal producers), equaling those of ~10 million cars or ~6 million homes. The underlying 595 PJ/year energy consumption ($11 billion/year) is on par with that of all other crop production, four times that of the pharmaceutical and medicine or beverage and tobacco industries, one-third that of data centers, and half again greater than that of cryptocurrency mining. National legalization alone would achieve only modest reductions, but it could enable more potent policies; the most promising avenue could reduce emissions by up to 76% by shifting more cultivation outdoors.

INTRODUCTION

Controlled environmental agriculture—the industrialized cultivation of plants indoors, often without sun, wind, rain, or soil—is a burgeoning practice.[1] The associated new technologies and practices result in consequences that are still being understood. Among these are elevated resource requirements, including energy inputs. Cannabis has become the most energy- and carbon-intensive crop as cultivation has shifted from open fields to indoors, covering an area of ~5 million square meters (~270 average Walmart stores) in the US. This physical footprint is greater than that dedicated to artificially lit food production and floriculture across the country.[2,3]

By 2022, half of US adults had tried cannabis,[4] with 22% (62 million people over age 12) using it that year.[5] Of these, 17.7 million used it daily or almost daily—more than those who drink alcohol at similar frequencies, although use rates across the entire population are about one-third lower for cannabis than alcohol.[6]

US sales of legal cannabis products are projected to reach $31 billion in 2024,[7] not including the value of cannabidiol (CBD) products (an additional ~$4 billion/year)[8] and home cultivation, valued at approximately ~$7 billion/year (see the supplemental information). This suggests that total annual sales are on the order of $100 billion, given that two-thirds of the ~24 kt/year production still occurs in the illicit market.[2] For reference, revenues

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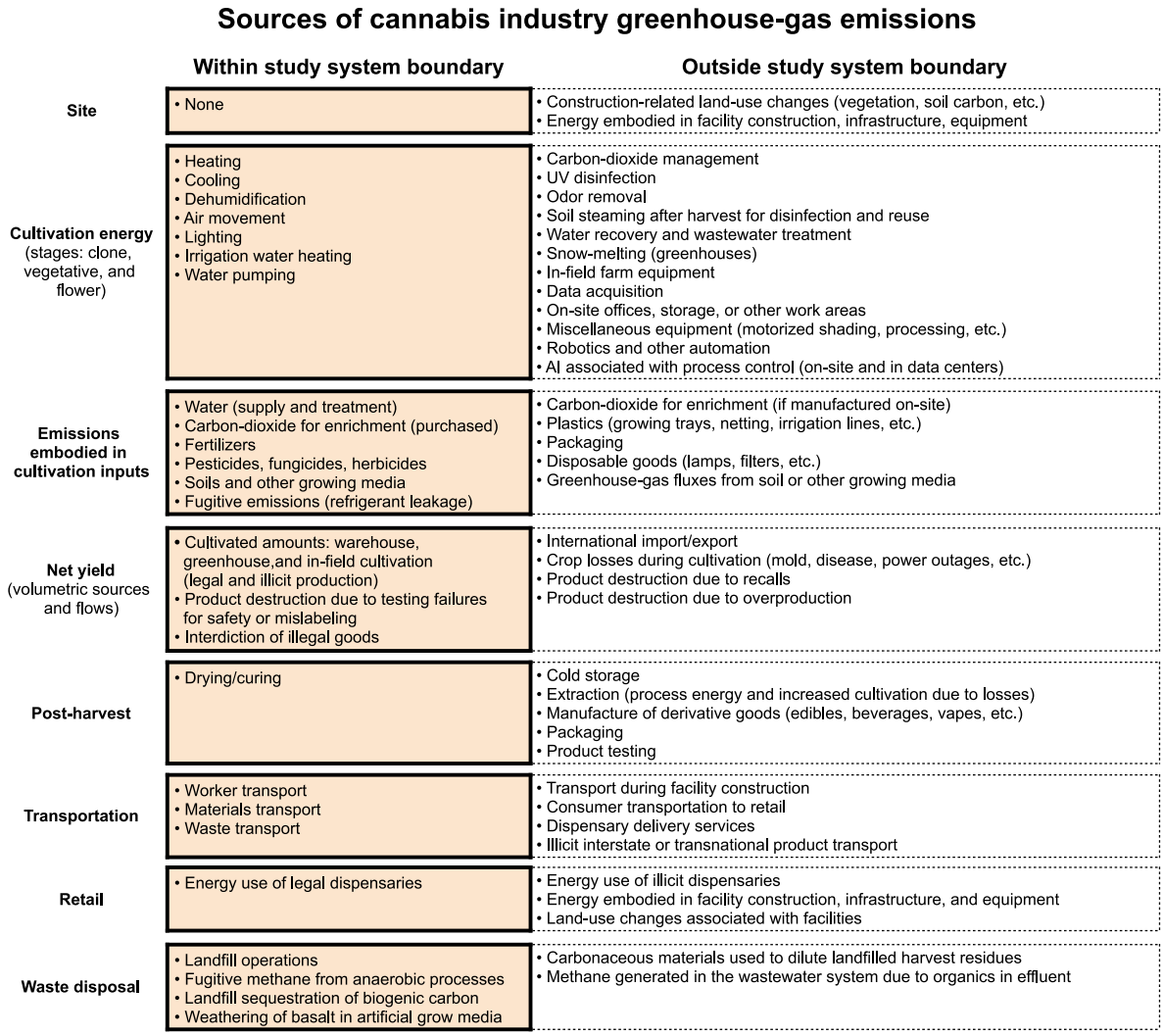
Sources of cannabis industry greenhouse-gas emissions
Within study system boundary
Outside study system boundary
Site
• None
• Construction-related land-use changes (vegetation, soil carbon, etc.)
• Energy embodied in facility construction, infrastructure, equipment
Cultivation energy (stages: clone, vegetative, and flower)
• Heating
• Cooling
• Dehumidification
• Air movement
• Lighting
• Irrigation water heating
• Water pumping
• Carbon-dioxide management
• UV disinfection
• Odor removal
• Soil steaming after harvest for disinfection and reuse
• Water recovery and wastewater treatment
• Snow-melting (greenhouses)
• In-field farm equipment
• Data acquisition
• On-site offices, storage, or other work areas
• Miscellaneous equipment (motorized shading, processing, etc.)
• Robotics and other automation
• AI associated with process control (on-site and in data centers)
Emissions embodied in cultivation inputs
• Water (supply and treatment)
• Carbon-dioxide for enrichment (purchased)
• Fertilizers
• Pesticides, fungicides, herbicides
• Soils and other growing media
• Fugitive emissions (refrigerant leakage)
• Carbon-dioxide for enrichment (if manufactured on-site)
• Plastics (growing trays, netting, irrigation lines, etc.)
• Packaging
• Disposable goods (lamps, filters, etc.)
• Greenhouse-gas fluxes from soil or other growing media
Net yield (volumetric sources and flows)
• Cultivated amounts: warehouse, greenhouse,and in-field cultivation (legal and illicit production)
• Product destruction due to testing failures for safety or mislabeling
• Interdiction of illegal goods
• International import/export
• Crop losses during cultivation (mold, disease, power outages, etc.)
• Product destruction due to recalls
• Product destruction due to overproduction
Post-harvest
• Drying/curing
• Cold storage
• Extraction (process energy and increased cultivation due to losses)
• Manufacture of derivative goods (edibles, beverages, vapes, etc.)
• Packaging
• Product testing
Transportation
• Worker transport
• Materials transport
• Waste transport
• Transport during facility construction
• Consumer transportation to retail
• Dispensary delivery services
• Illicit interstate or transnational product transport
Retail
• Energy use of legal dispensaries
• Energy use of illicit dispensaries
• Energy embodied in facility construction, infrastructure, and equipment
• Land-use changes associated with facilities
Waste disposal
• Landfill operations
• Fugitive methane from anaerobic processes
• Landfill sequestration of biogenic carbon
• Weathering of basalt in artificial grow media
• Carbonaceous materials used to dilute landfilled harvest residues
• Methane generated in the wastewater system due to organics in effluent

Figure 1. System boundary for estimating the US cannabis industry's carbon footprint and factors included in this study

from corn were $89 billion in 2022.[9] As another indicator of scale, industry sources report 165,400 legal cannabis businesses operating across the US,[10] employing approximately 440,000 people.[11]

As federal lawmakers edge toward cannabis reforms, drug policy inadvertently finds itself at cross purposes with climate and energy policies. These dynamics have been largely overlooked, and the single peer-reviewed estimate of the industry's energy-related carbon footprint is more than a decade old, placing the national greenhouse gas emissions at 15 Mt CO_2e/year (equivalent to those of 3 million average cars).[12] Policymaking is thus being conducted without a clear grasp of the problem's current dimensions.

The present update identifies substantial recent growth in emissions, driven by the combination of elevated production levels and dramatic structural changes in the industry toward more energy-intensive cultivation methods. Disaggregating emissions into multiple sub-categories helps with pinpointing areas of specific relevance, developing quantitative analysis of future emissions pathways for a range of technology and policy scenarios, and identifying remaining data gaps and research needs.

In this analysis, "cradle-to-grave" greenhouse gas emissions are estimated for activities spanning cultivation, agricultural inputs, transport, retail, and waste disposal, building upon a previous life cycle assessment of cannabis cultivation in legal warehouse-type structures hereafter referred to as "plant factories."[13] The analysis significantly broadens the system boundary (Figure 1), allowing for a more comprehensive and nuanced emissions assessment that distinguishes among plant factories, greenhouses, open-field methods, and home cultivation while extending prior building-level results to the national scale, with separate treatment of legal and illicit cultivation practices, and providing a far broader array of indicators (e.g., national energy expenditure). This new work integrates extensive modeling studies and empirical data not available when the original 2012 assessment was conducted. The resulting estimated aggregate emissions are greater than those of several major industries and

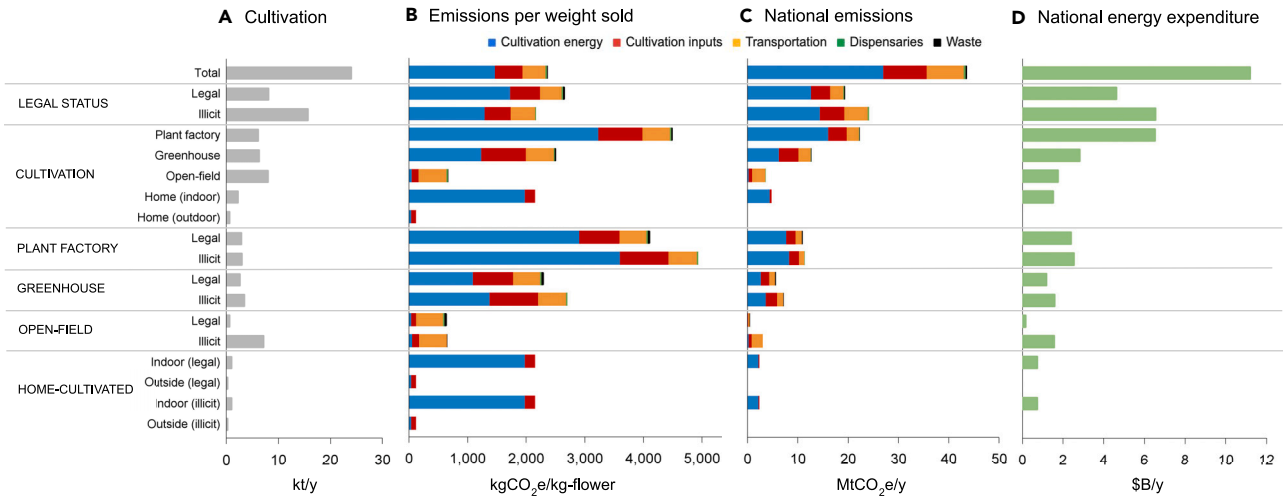

Figure 2. US cannabis production, normalized emissions, aggregate emissions, and energy expenditures by cultivation method and legal status (2023)

The higher per-weight amounts for illicitly grown cannabis are driven primarily by 5% of electricity production by off-grid diesel generators and eradication losses. With severe overproduction in the current market, the emissions per weight sold could be significantly higher across all categories. Values include energy use at the point of consumption, with electricity counted at 8.2 MJ/kWh. Data are shown in Tables S1 and S3–S7.

represent a significant part of individual consumers' carbon footprints. Emissions have risen substantially despite widespread state-level legalization efforts, which suggests that relying on market forces alone is not a viable climate strategy for this industry. More targeted policy initiatives are needed to manage emissions, and the greatest potential lies in guiding the industry toward a much larger share of open-field cultivation.

RESULTS

A growing carbon footprint

National emissions are determined by applying measured facility-level field data and model results to the corresponding production volumes and market segments. Specific sources of emissions considered include energy used directly in the cultivation process (Table S3) and embodied in growing media (Table S5), agricultural inputs,[13] and water supply; energy used at retail dispensaries (Table S6), associated with the transport of materials, workers, and waste; and fugitive emissions from leaking space-conditioning equipment refrigerants[14] and landfill-related methane releases from the decomposition and sequestration of carbon in buried biomass (Table S7). Not all sources of emissions could be quantified, reflecting a lack of data or reliable estimation methods.

Aggregate greenhouse gas emissions from the US cannabis industry reached ~44 Mt CO_2e/year in 2023 (Figure 2C). This represents 1% of total national emissions from all sectors of the economy and corresponds to an annual energy expenditure of ~$11 billion. The results are segmented by industry activity, facility type, and legal status (Figure 2; Table S1).

At the national level, energy used in the cultivation process is the dominant source of emissions (63% of the total), followed by emissions embodied in the manufacture of cultivation inputs (20%), transportation (17%), waste management (<1%), and retail dispensaries (<1%), with these shares varying widely depending on cultivation method and other factors (Tables S3–S7). Products cultivated without the assistance of daylight in plant factories and indoor home locations are associated with 62% of the industry's emissions, 29% for cultivation in greenhouses, and 9% for cultivation in open fields. Illicit operations produce 55% of total emissions, much less than their market share of flower production, thanks primarily to a larger proportion of open-field cultivation.

Cannabis energy demand and emissions are rising. The current estimate is three times greater than one published 13 years earlier.[12] After adjusting for system boundary differences between the two studies (the earlier of which analyzed plant factories only), the net effect is a 2.6-fold increase in overall emissions. During this period, a 40% reduction in per-unit electricity emissions from a progressively cleaner power grid offset some emissions growth; however, these gains were overwhelmed by a 1.4-fold increase in harvests and a nearly 5-fold increase in amounts grown indoors.

The corresponding average 2023 carbon emissions for commercial operations is ~4,500 kgCO_2e/kg-flower for plant factories, ~2,500 kgCO_2e/kg-flower for greenhouses, and ~700 kgCO_2e/kg-flower for open-field cultivation (Figure 2B). Due primarily to differences in energy mix, the average emissions of illicit operations are higher than those of legal ones. Less-intensive home cultivation produces roughly 2,150 kgCO_2e/kg-flower, half of plant factory emissions levels (Table S3).

Fueling the underlying intensive energy requirements, the indoor environment in plant factories is maintained at clear-sky tropical conditions, irrespective of the outdoor climate or time of day or year. Artificial lighting levels are brighter than the sun. Air is mechanically conditioned and often recirculated at 30–60 times the rate of that in homes, and dehumidification is essential to preempt mold growth, while other energy-intensive processes such as water purification and odor mitigation technology further elevate energy use. Industrial greenhouses

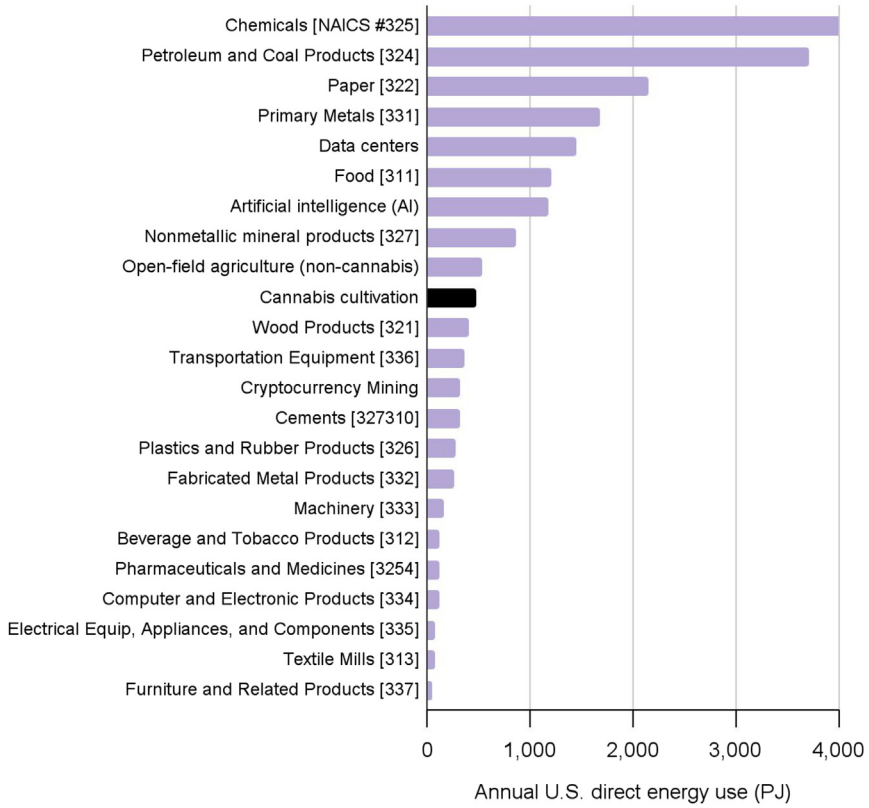

Figure 3. Energy use for cannabis cultivation in context with that of other US industries

Values for the non-cannabis sectors include direct on-site uses of fuel and electricity in the production process at US-based facilities, with electricity counted at 8.2 MJ/kWh. For comparability to other sectors, the values for cannabis include only those associated with cultivation and post-harvest processing, excluding energy embodied in inputs or that from retail activity, transportation, or waste disposal. Data are shown in Table S2.

heavily augment daylight with electric lighting, and their poor insulation and large glazed areas typically create significant air conditioning and heating needs. To accelerate plant growth, energy-intensive CO_2 enhancement maintains indoor levels 2–4 times outdoor ambient concentrations, which, together with other non-energy inputs, further increases embodied greenhouse gas emissions. In sum, cultivating a given amount of cannabis indoors results in approximately 30 times more emissions per kilogram than cultivating outdoors. When incorporating emissions from all other stages of the life cycle, cannabis cultivated in plant factories is 7 times more emissions intensive.

Indoor cultivation is also far more energy intensive than more familiar building types and manufacturing processes. For comparison, while a typical cannabis plant factory is similar in size to an average Walmart, it uses ~100 times more energy. Energy use per unit floor area is ~600 times that of conventional storage warehouses and ~40 times that of energy-intensive hospitals. Energy use per unit weight is ~200 times that of manufacturing best practices for aluminum, ~2,200:1 for blast furnace steel, and ~10,500:1 for Portland cement.

For further context, a set of equivalencies computed in Table S2 compares cannabis energy and emissions to national energy use, a wider variety of other building types, conventional agriculture, and a number of familiar activities ranging from diet to driving. Among these comparisons, the cannabis industry produces greenhouse gas emissions equivalent to those from ~10 million average cars or ~6 million US homes. The carbon footprint of energy use for cultivation in cannabis plant factories (per unit weight) ranges from 200 to 700 times that of cultivating lettuce and other common crops in similar facilities,[15] and accordingly, cannabis production nationally is comparable to the aggregate energy use in conventional indoor and open-field agriculture (excluding the livestock, poultry, and dairy segments) (Table S2).

The associated energy use can be compared to that of other industries (Figure 3). The direct, on-site use of fuels and electricity by the cannabis industry is 4 times that of domestic use by the US pharmaceutical industry and beverage and tobacco manufacturing. Energy use is a third of what is used by data centers nationally, and 1.5 times that of cryptocurrency mining, topics that have garnered considerable attention.[16]

From the individual's perspective, emissions associated with the average annual cannabis consumption are equal to 11% of the average home's energy-related emissions, rising to 24% for the average weekly consumer and 43% for the average daily or near-daily consumer. Emissions for this latter group (assuming cultivation in plant factories) are 105% of those associated with the average American diet and 155% of a healthy vegetarian diet, while values for the average cannabis consumer are 26% and 38% of the average diet, respectively.

Enormous potential exists for emissions reductions, but there is also a risk of increases

Market evolution and policy choices will significantly influence future emissions trajectories (Figure 4). Key upward pressures include rising demand for cannabis, changes in industry structure, reversion of legal producers to the illicit market (where electricity sources can be dirtier and less efficient) in response to what are perceived as overzealous regulations, and a trend toward derivative products[17,18] that embody added processing energy. For example, if 50% of sales are eventually conveyed to consumers by delivery services, then emissions would rise by 4% (1.5 Mt CO_2e/year). Reducing the emissions of industry vehicles by three quarters would lower overall emissions by 13% (5.5 Mt CO_2e/year). If 25% of open-field cultivation shifted indoors, then emissions would increase by 10% (4.5 Mt CO_2e/year). A 25% increase in cultivation energy resulting from new processes (e.g., increased artificial illumination, wastewater recovery, and automation) would increase overall emissions by

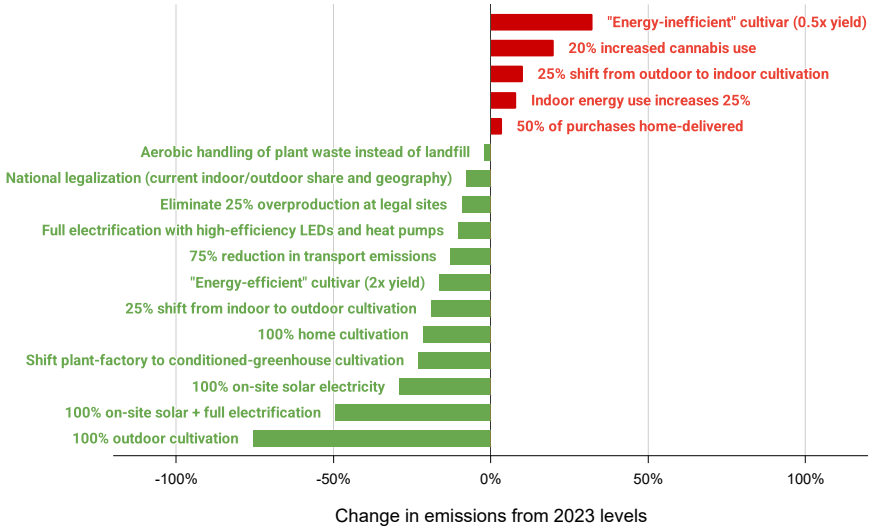
"Energy-inefficient" cultivar (0.5x yield)
20% increased cannabis use
25% shift from outdoor to indoor cultivation
Indoor energy use increases 25%
50% of purchases home-delivered
Aerobic handling of plant waste instead of landfill
National legalization (current indoor/outdoor share and geography)
Eliminate 25% overproduction at legal sites
Full electrification with high-efficiency LEDs and heat pumps
75% reduction in transport emissions
"Energy-efficient" cultivar (2x yield)
25% shift from indoor to outdoor cultivation
100% home cultivation
Shift plant-factory to conditioned-greenhouse cultivation
100% on-site solar electricity
100% on-site solar + full electrification
100% outdoor cultivation
-100%
-50%
0%
50%
100%
Change in emissions from 2023 levels

Figure 4. Industry-wide emissions impacts from changes in policy and market structure

Values apply to aggregate emissions from all forms of production (plant factory, greenhouse, and open field) and all segments (commercial/home and legal/illicit), including energy use, cultivation inputs, dispensaries, transportation, and waste disposal (baseline emissions of 44 Mt CO_2e/year). "Indoor" refers to conditioned greenhouses together with plant factories and indoor home cultivation. Note that the "full legalization" case does not model the possible effects of relaxing restrictions on interstate commerce or other policies that could be deployed in a legal market. The electrification, solar, and reduced transport emissions cases are technological thought experiments, irrespective of a cost-benefit analysis that would likely moderate these changes. The scenario values are not additive.

8% (3.5 Mt CO_2e/year). Choice of cultivar (sometimes loosely referred to as "genetics," "strain," or "variety") is a major source of variability (Figure 5), ranging from a 32% (14.1 Mt CO_2e/year) emissions increase to a 16% reduction (7.1 Mt CO_2e/year).

Potential moderating factors include manufacturer shifts away from indoor cultivation in response to regulatory changes, economic and reputational risks, decarbonization initiatives, increased transport efficiencies, and improved waste management practices. Meeting all existing electricity demands for cultivation with on-site solar would achieve a 29% emissions reduction (12.6 Mt). Conversely, full electrification plus trimming energy use via universal adoption (a stretch goal) of key energy efficiency technologies (unmoderated by cost-benefit considerations), such as light-emitting diode (LED) lighting and heat pumps, would achieve a 10% reduction (4.4 Mt CO_2e/year). Combining solar and electrification would increase these reductions to 49% (21.5 Mt CO_2e/year). Interestingly, in the solar-plus-efficiency case, some emissions remain due to the leaking of fugitive refrigerants, which are potent greenhouse gases, as well as a small amount of diesel fuel that continues to be used at off-grid locations where large solar systems are not practicable.

Technical nuances

Energy use and greenhouse gas emissions are key indicators and normalized by the functional units of cultivation area or the weight of the finished "flower" reaching consumers to create efficiency or productivity metrics. The resulting intensities, e.g., MJ/m^2-year, GJ/kg-flower, and CO_2e/kg-flower, vary systematically by cultivation method. They are applied to production volumes for scale-up to national energy use, emissions, and expenditures (Table S1). Weight-based metrics are useful for assessing and comparing production method use, while area-based metrics are useful for energy infrastructure planning at the facility and grid levels, as well as the scale of generation required for on-site energy production. Metrics of energy per unit product potency (Figure 5C) are more precise and useful in comparing energy inputs across different methods of processing but are very rarely provided in the literature.

Modeling and precision benchmarking of measured field data each yield important insights. The judicious use of these methods is valuable for facility designers, operators, and policymakers (discussed further in the supplemental information). Measured field data provide real-world insights that model-based analysis may not, an essential check on model accuracy, and opportunities to validate and calibrate models or create "digital twins" for making energy savings estimates. Cannabis field studies, however, are unstandardized, vary widely in quality and rigor, and are often poorly documented, especially in terms of the extent of the system boundary being evaluated.[21] The present analysis draws on an exhaustive literature review that yielded measured energy use estimates for 325 sites or trials at given sites and an additional 15 modeling studies (Figures S1 and S2).

The confluence of horticulture and energy issues makes for fascinating and sometimes surprising analyses, such as the non-proportionality of energy inputs and yields, evidenced by a 5-fold variation in energy requirements as a function of plant cultivar and significantly varying benefits of energy efficiency strategies such as LED lighting even for a particular cultivar (Figure 5), and the large role played by local climate and operational variables.[13]

Additional analytical subtleties are evident in that the highest modeled normalized carbon footprint (5,184 kgCO_2e/kg of finished flower[13]) for plant factories in a model-based study spanning all 50 states occurs in Hawaii, a climate normally thought of as well suited for high-quality open-field cannabis cultivation. Cultivating indoors there entails intense dehumidification and air conditioning in a hot climate compounded by the heat generated from high-wattage lighting, together with one of the country's highest electricity emissions factors nationally due to an electricity grid heavily dependent on oil.

As detailed in the supplemental information, applying emissions intensities to obtain aggregate (e.g., national) estimates begins with estimating national cannabis production and consumption; adjusting for second-order adjustments arising from crop failure, eradication, and post-harvest seizures; and products destroyed following consumer safety tests. The

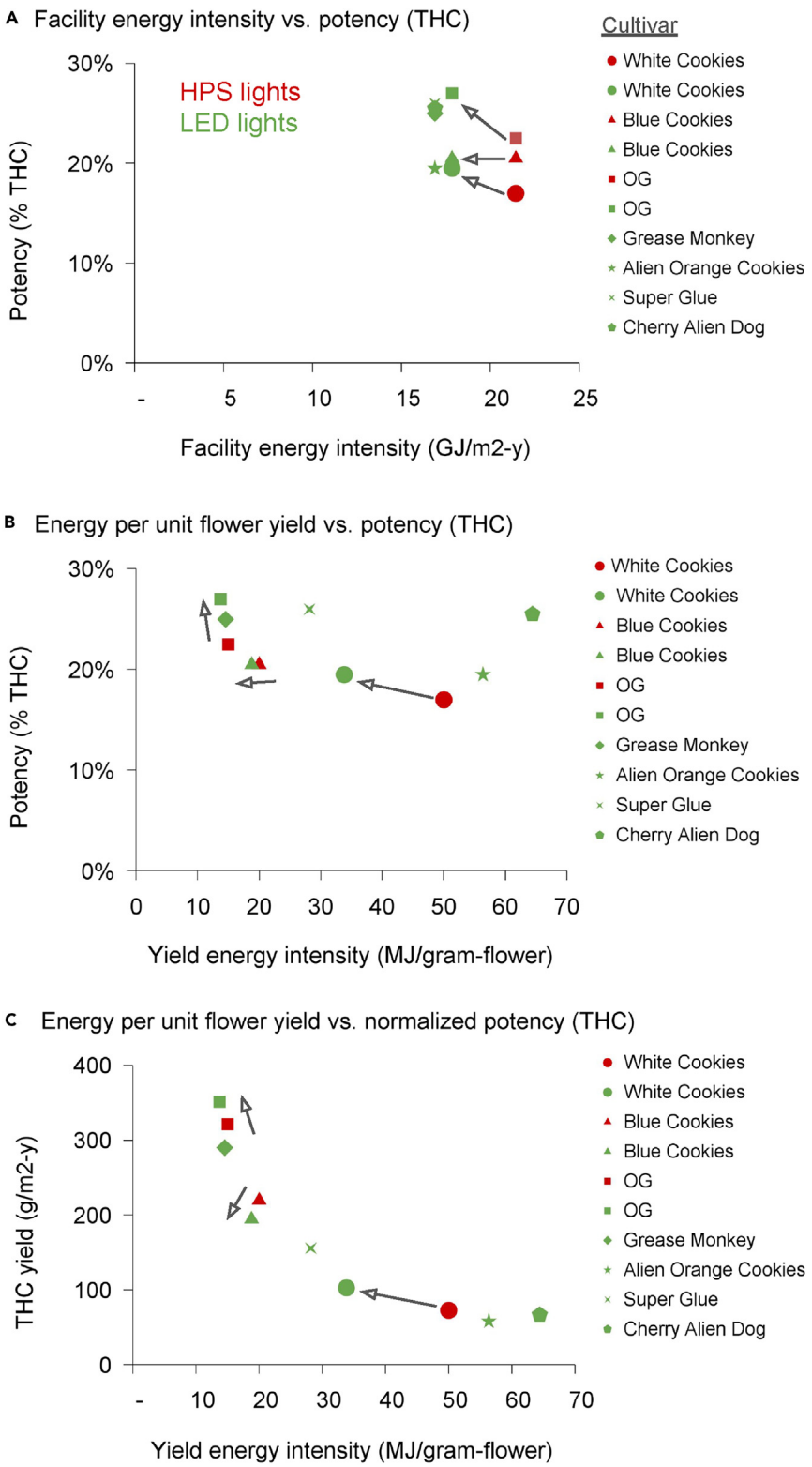

Figure 5. Ten cannabis plant factory cultivation trials with HPS versus LED lighting and seven cultivars

Lighting technologies: 1,000-W Nanolux Super DE high-pressure sodium (HPS; in red) and 660-W Fluence SPYDRx PUS light-emitting diode (LED; in green). Arrows indicate changes for the switch from HPS to LED for three paired cultivars, with energy savings per unit weight of finished flower ranging from 32% in one case to 9% and 6% in the remaining two cases.[19] Energy per THC (active ingredient) declined by 41%, 6%, and 24%. Four other cultivars were grown under LED only. Another study[20] found higher energy use per unit weight for cultivation under LED lights.

combined effect of these factors is that final consumption is about ~20% less than gross cultivation, making the energy intensity of the product ultimately sold correspondingly higher. After these adjustments, energy use and emissions are allocated to 18.4 kt of cannabis flower ultimately reaching the market either directly or via derivative products.

Uncertainties and sensitivity analysis

Emissions would be higher were the processes outside the system boundary shown in Figure 1 incorporated. A few of those possibilities can be tested, e.g., the impacts of land-use change in forested areas (Table S8) and emissions associated with post-harvest extraction of active ingredients, although most lack sufficient data for in-depth evaluation and scale-up to the national level. Of particular interest, a scoping calculation of emissions from the common supercritical CO_2 extraction process to obtain oils for sale in the market or incorporation in derivative products suggests a non-trivial 11%–31% increase in total emissions per kilogram (Table S9).

With respect to estimates of energy use within the cultivation process adopted here from Summers et al.,[13] the greatest modeling uncertainties influencing facility-specific emissions, in order of decreasing importance, are the plant yields per unit cultivated area, hourly air change rates (ACHs), and the levels of supplemental carbon dioxide. Reductions in plant yields increase emissions per unit weight, implying more cultivation area (and associated energy use) to meet national production targets.

There are various noteworthy market uncertainties. Cannabis production levels and practices in the illicit market are less well characterized than those in the legal market, which are ostensibly reported to regulators and the trade press. While energy intensities for illicit

producers may well be higher than those developed here for legal operations, there are no public domain measurements to guide a more nuanced assessment, so here they are assumed to be identical. Importantly, no allowance for overproduction is built into the emissions-intensity estimates, in which event emissions per unit of product reaching consumers would increase proportionately. As outlined in the supplemental information, however, overproduction is considerable in many parts of the country, as well as Canada.

Sensitivity analyses suggest robust findings insofar as they are well within the broad magnitudes of potential emissions reductions from most policy interventions (Figure S3). Cautious estimates have been adopted for analysis where multiple data sources are available.

DISCUSSION

Modeling how emissions *will* evolve is trickier than how they *might* evolve. Absolute emissions would rise with one-to-one proportionality were cannabis demand to increase and cultivation practices to remain the same. The prime driver toward lower energy intensity and emissions would be a substantial regulated or voluntary shift from indoor-grown to open-field cannabis. Indoor energy use could also be managed downward, but there is low interest among facility operators in energy efficiency and real limits to how much energy can be cost effectively saved or how much renewable energy could be applied. There are strong countervailing factors, including structural, market, and regulatory biases that favor indoor cultivation and a continuing trend toward the replacement of labor with machines and more energy-intensive indoor processes. Persistent gaps in available market data impede the quantification of these effects at national scales.

Potential drivers of increased open-field cultivation

Open-field cannabis cultivation is well established and, until the 1970s, was essentially the only method in use. Inducements to cultivate outdoors include legalization, substantially lower capital and operating costs thanks primarily to less expensive land, and the absence of energy-using equipment. Open-field cultivation also entails less waste in the form of spent lamps, artificial growing media (typically replaced with each cultivation cycle), assorted plastics, and contaminated wastewater. Furthermore, depressed product prices have put cultivators under severe economic stress, which has made the energy costs of indoor cultivation (often ~40% of total operating expenses) highly problematic and raised solvency risks for indoor cultivators, particularly in the off-grid illicit market, where costly diesel generators are often required. Increased product prices would reduce the role of energy in profitability and, thus, could reverse this trend.

A key factor shaping the extent of open-field cultivation in recent years has been a shift in consumer preferences toward extracts typically obtained from cannabis cultivated outdoors, a use for which flower appearance is unimportant to consumers. Between 2018 and 2023, marking a shift toward products based on extracts, the number of American consumers choosing cannabis flower dropped from 80% to 70%.[18] Among the products made with extracts, only edibles showed a marked upward trend (41%–59% of consumers), while other forms (concentrates, vape oils, topicals, tinctures, etc.) held roughly constant market shares. Whether this trend will continue and how growth in overall demand might offset any reduction in emissions per unit of consumption is unclear.

A shift toward consumer interest in the "green" attributes of cannabis products would also favor open-field cultivation, but there is little evidence of this at present. Instead, the dominant preference is for cosmetically appealing and higher-potency indoor-grown flower. Lack of consumer information, such as product labeling, certainly impedes environmentally based consumer decisions and increases vulnerability to greenwashing, and salespeople and other industry actors have also demonstrated low literacy about such matters.[22]

Potential drivers of increased indoor cultivation

In recent years, the cannabis industry has experienced profound structural change, including higher-intensity indoor cultivation at increasing scales. Perhaps counterintuitively, indoor cultivation expanded markedly following legalization at the state level. The share of indoor cultivation rose from ~33% in 2012[12] to ~65% in 2023[2] while widespread legalization ushered in an increased demand (up 142% since 2012)—implying a nearly 5-fold increase in the quantity grown indoors—together with a tripling in potency since 1995.[18] Today, indoor cultivation in the US—particularly in plant factories—is more common for cannabis than for any other field crop.[2,3] Eradication reports[23] demonstrate the presence of indoor cultivation in 32 of the 37 states—and one in five total sites—showing that illicit cultivation also commonly occurs indoors.

Drivers of indoor cultivation beyond secrecy and security include precision control, crop standardization, weather protection, steady production throughout the year (four to six harvests are typical), avoiding rogue pollen from male plants that can ruin a crop, increased potency, and local prohibitions on open-field cultivation. Desirable cosmetic appearance combined with preferential marketing have led to retail prices for indoor-grown products that are about twice the level of those for outdoor-grown products. Although a commonly stated rationale for indoor cultivation, medical and quality-related attributes of indoor-grown cannabis are not clearly superior by these measures,[24,25] fungus outbreaks can be more common,[26] and the marginally higher potency is not necessarily healthful.[27] Meanwhile, the prospect of enormous permitting revenues incentivize cities to promote urban cultivation, which must almost universally be done indoors.

Inertia to improved energy efficiency, electrification, and uptake of onsite renewable energy

Although cannabis—legal and illicit—is the largest US cash crop by value, the uptake of energy-saving measures in the indoor agriculture industry is slow, e.g., LED lighting is serving only 2% of lighting-supplemented greenhouses and 11% of plant factories.[3] This is perhaps a reflection of sinking profits and short financial planning time horizons. More than half of growers in one Colorado survey reported requiring at least a 33% return on energy-saving investments, while few measures evaluated for that same area offered such returns.[28] Creating further inertia, proposed mandatory requirements for LED lights have been met with industry skepticism and opposition,[29,30] and such

equipment still uses prodigious amounts of energy. Perhaps fueling these concerns, one comparative assessment[19] (Figure 5) found widely varying savings from LED lights. Meanwhile, a recent study projected a meager ~10% energy savings "technical potential" for the full penetration of all viable measures—whether cost effective or not—for cannabis facilities in Canada and the US.[31]

Renewable energy has its own considerations and constraints. Covering conventional cannabis plant factory rooftops with solar panels would meet only ~5% of electricity needs for typical cultivation practices.[32] Full conversion to solar photovoltaic energy to serve existing cannabis producers' electricity needs nationally would require 33,000 ha (127 square miles) of land (many times that otherwise needed to produce the same yields with open-field cultivation), rising to 46,000 ha (178 square miles) were the sector to fully electrify (the only path to net zero emissions) (Table S2). Moreover, diverting finite renewable energy to indoor cannabis producers would slow progress toward decarbonization, particularly in light of growing electricity demand from electrification efforts and other expanding activities, such as artificial intelligence (AI), thereby contributing to delays in retiring fossil fuel power plants. For perspective, cannabis development under remaining entitlements in the southern California Coachella Valley desert communities would exceed the state's entire production of electricity from wind power.[32]

Of broader relevance to decarbonization goals, indoor cannabis cultivation is not particularly "grid friendly." The industry's current electricity use (35 TWh/year) is equivalent to 9 GW or the output of 12 typical electric power plants (Table S2). Unanticipated load spikes straining electrical infrastructure can lead to outages also affecting nearby customers (Table S10). Industry expansion and substitution of fuel with electricity to decarbonize will further elevate peak loads. Small producers are not readily able to shift operations to different times of day, and many larger producers have already diversified their load (to reduce costs) and remain highly constrained by the required continuous 12–18 h/day on times for lighting.[29] Electricity theft, industry expansion, and market volatility further complicate long-term utility planning.

Identifying optimal pathways

Given the specter of rising damages from human-caused climate change and the narrow potential for energy efficiency and renewable energy in this industry, excessive greenhouse gas emissions from indoor cannabis production are arguably a luxury that society cannot afford. Meanwhile, wise federal policymakers will also recognize that the boom-and-bust risks already manifesting in the industry are likely attributable, in part, to high energy costs.

Further fine-tuning the energy efficiency of indoor cultivation optimizes the suboptimal, in that there is no demonstrated path through which the indoor industry's emissions could be reduced to align with national climate stabilization targets. Reverting to conventional open-field cultivation methods—particularly as done in the illicit market when environmental protections are disregarded[33–35]—would achieve deep emissions reductions but could also produce environmental impacts, albeit many of which are avoidable via improved practices. Thus, as with many forms of agriculture, a more sustainable model for open-field cultivation is needed. The conventional wisdom that indoor production is less water and land intensive hinges on analyses with overly narrow system boundaries together with "apples-and-oranges" comparisons of highly optimized indoor cultivation with inefficient open-field methods based on a legacy of lower land costs and inexpensive or even free water. When both methods are optimized, open-field cultivation requires less of these resources per unit of final product (Figures S4 and S5).[36] Comparisons often assume only one open-field crop per year, while under ideal conditions, up to three can be achieved. Importantly, when accounting for water embodied in power production and additional land required for decarbonization via renewable energy production, even conventional open-field cultivation methods are less resource intensive.

A shift to purely open-field cultivation—following best practices for water and land use and employing other environmental safeguards—would achieve 76% (39.9 Mt CO_2e/year) emissions reductions. Even with current unoptimized cultivation methods, only 0.003% of American farmland would be required to meet the national demand in that scenario, which is similar to that already in cultivation for hemp. This is the most elegant solution.

In addition to climate benefits, with sustainable open-field cultivation, a set of related environmental issues are intrinsically addressed. These include hazardous wastes such as mercury in lamps, water use, occupational safety risks arising from indoor pollution in grow facilities, light and noise pollution, nuisance odors, and other emissions into heavily populated airsheds.[32,37]

The potential role of legalization

Legalization is often invoked as the means for solving problems in the cannabis industry. As of November 2024, 38 states, the District of Columbia, and four US territories had legalized cannabis for medical or recreational use.[38] Four additional states had decriminalized cannabis, and nine others allowed low-tetrahydrocannabinol (THC) products.[38] This advanced state of legalization offers a natural experiment with regard to greenhouse gas emissions impacts, although clearly the prospect of federal legalization has separate implications.

The first-order impacts of successful legalization—assuming all illicit producers transition to the licensed operations—would be the cessation of interdiction and the significant lost embodied energy in products that are subsequently destroyed, along with the reduced use of diesel-powered electricity generation in off-grid locations in favor of an electric grid that is cleaner in most areas. Offsetting factors would include increased energy use from replacing products destroyed following legally mandated safety testing, more regulated landfills of cultivation waste and the associated emissions, and more brick-and-mortar dispensary facilities with their associated energy use. Any incremental impact would be further moderated by the fact that half of illicit cultivation is already conducted outdoors.[2] The net effect of these factors is relatively modest direct emissions reductions of 8% (3.3 Mt CO_2e/year), assuming no geographic shift in cultivation.

In the event that interstate transport bans were lifted, related questions would be whether states with climates that do not favor open-field cultivation (albeit seasonal open-field cultivation does occur in all states) would opt instead to import from states where it is more feasible (and where indoor cultivation is also less

energy intensive) and to what extent this benefit would be attenuated by existing large volumes already flowing over state lines from these locales via the illicit market. As indicators of the scale of illegal exportation, at one time, California was estimated to be producing ~7,000 t/year of cannabis while consuming only ~1,000 t in state,[39] and licensed production in Oklahoma exceeded in-state demand through the legal market by 32-fold.[40]

About two-thirds of the nation's current legal production already occurs in states with mild climates, yet indoor cultivation there remains widespread. As a prominent illustration, recent estimates suggest that California produces 45% of the nation's (legal and illicit) cannabis, much of which is grown indoors.[41] Were the geography of cultivation to recalibrate based on climate, shipping distances would increase, especially to markets that have, for decades, deemed products from western states to be superior, although the reduction of existing long-distance illicit transport (not quantified in this study) would offset that to some degree, perhaps significantly. These factors notwithstanding, second-order benefits of legalization could be very large, resulting from additional policies that can only be applied in legal markets.

Particularly vexing, experience to date suggests that illicit markets remain strong even where cannabis is legalized, thanks to retail prices that may be doubled by layers of taxation, onerous and costly licensing and reporting processes, mandatory product testing, retail restrictions, scarcity of banking and insurance services, and opposition of local governments to cultivation or sales.[42]

Policy prescriptions

National energy use and greenhouse-gas emissions associated with cannabis cultivation are on par with those of all other crops, yet it is rarely addressed by policymakers. This assessment suggests that rebalancing production in favor of open-field cultivation is the most promising policy measure for reducing these impacts. Despite its potentially low direct impacts, full legalization in the remaining twelve states, and federally, is essential to deploying and scaling up more impactful policies and structural changes such as those outlined in Figure 4.

Free markets are often touted as ensuring economic efficiency (a precursor to energy efficiency), but other studies suggest that cannabis markets are not, in practice, functioning in this manner following state-level legalization.[43] This appears to be borne out in the case of energy resources as well. Some existing policies in legalized markets exacerbate the problem, including resource-intensive packaging regulations that increase waste volumes[44]; multiple forms of subsidies or market distortions that differentially reward indoor cultivation, including hefty utility "rebates" for indoor facilities that attain small energy savings, while no incentive is offered for open-field operations saving vastly more[32]; and fee structures and grants that preferentially benefit indoor cultivators. Some states that have legalized cannabis prohibit cultivation outdoors, and some selectively require that only home cultivation be conducted indoors, while others make varying decisions at the local level, e.g., as seen by jurisdictions prohibiting open-field cultivation across about half of California's land area.[45] Meanwhile, state-level legalization has triggered overproduction (see supplemental information) and a shift toward indoor facilities, both of which boost energy use appreciably while fueling retail price drops[18] that, in turn, make it harder to justify investments in decarbonization. For context, if overproduction among legal commercial producers was currently at the hypothetical level of 25%, then rebalancing the market would directly yield 9% emissions reductions (4.0 Mt CO_2e/year).

Another defining issue is that large-scale legal indoor cultivation is increasingly concentrated in environmentally overburdened urban areas, as seen in Oakland and Denver, each of which host about 200 sanctioned plant factory operations. Measured emissions of potentially unhealthful volatile organic compounds (biogenic from cultivation and non-biogenic from solvent-based extraction) within a mile of the facilities have been found to be 4–8 times higher than the already-elevated background levels due to nearby transportation corridors and petroleum industry activity and hundreds-of-fold higher inside.[46,47] Producers located in these settings have also been cited for the illegal use of large diesel generators. One resulting concern is environmental justice, where workers and citizens most affected by the harms of indoor cultivation are disproportionately non-White and of lower income.[48] It is a troubling irony that these are the same populations often highlighted as victims of incarceration for past cannabis-related crimes.

Further dampening progress, the information environment is remarkably devoid of communication about the environmental profile of cannabis products—impeding market forces that otherwise might drive change. Examples of information that may be material to consumers include that the 4.5 kg emissions underlying a 1-g, plant-factory-grown "pre-roll" equal those from driving the most efficient plug-in hybrid 105 km (65 miles). Conversely, the average daily or near-daily cannabis consumer's emissions are equivalent to driving 8,411 km (13,500 miles) in an average car. On a per-weight basis, emissions are about 320 times that of producing cigarettes (Table S2). Analysts also lack important information. The fragmentation of cannabis markets, uneven state-level regulations, and proprietary treatment of producers' energy data, together with a large and persistent illicit market and lack of a unified national statistical profile of the industry, create a challenging context for policymakers.

There is much science to be done. However, while the constraints federal cannabis laws impose on medical research are widely recognized,[18,49] US federal agencies are reported to be barred from funding research on the energy and climate impacts of cannabis cultivation.[50] State-level cannabis research focuses almost exclusively on medical questions and environmental issues stemming from open-field cultivation. This state of affairs hampers progress on rigorous public domain data collection and peer-reviewed analysis. The collection and disclosure of data relevant to energy and environmental analysis by regulators and other state and local authorities is uneven and incomplete. If these obstacles can be overcome, then particularly promising research and development (R&D) frontiers include expanding the system boundary for life cycle assessments (Figure 1), improving analyses of indoor- versus outdoor-grown cannabis product quality attributes, understanding the role of cultivar choice in carbon emissions, clarifying the effect of improved energy efficiency on yields, quantifying the potentially significant additional carbon footprint of producing extracts (Table S9) and other derivative products, understanding the environmental and social dimensions of air quality impacts, bringing more

rigor and efficiency to sustainable open-field cultivation, and probing the behavioral economics of consumer choices vis-a-vis sustainability.

Meanwhile, this research vacuum and the ongoing ineligibility of this industry for federal incentives to improve practices suggest voids that could be usefully filled by local jurisdictions. At the local and federal levels alike, and considering the large effect of cannabis consumption levels and product type on emissions, it is high time for drug policy and environmental policy to be harmonized.

METHODS

Details regarding the methods can be found in the supplemental information.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Evan Mills (evanmills1@gmail.com).

Materials availability

This study did not create new reagents, nor are there restrictions on the materials used.

Data and code availability

The original contributions presented in the study are included in the article and supplemental information, and further inquiries can be directed to the corresponding author.

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DECLARATION OF INTERESTS

The author declares no competing interests.

SUPPLEMENTAL INFORMATION

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